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Eddy Covariance Method for CO_2 Emission Measurements in CCUS Applications: Principles, Instrumentation and Software

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Abstract

The eddy covariance method is a micrometeorological technique for direct measurements of gas transport between the surface and the atmosphere. It is widely used for quantifying CO_2 emission rates from natural, urban and agricultural ecosystems, including areas of agricultural carbon sequestration. In geological carbon capture, utilization and sequestration, emerging projects utilize eddy covariance to monitor large areas where CO_2 may escape from the subsurface, to detect and quantify CO_2 leakage, and to improve CO_2 storage efficiency. This paper describes key principles of the method, main requirements, typical instrumentation and software, and educational resources particularly useful for carbon sequestration research.

Keywords: eddy covariance, CO_2 emission, carbon sequestration, CCS, CCUS

1. Introduction

The eddy covariance method is a micrometeorological technique for direct high-speed measurements of the transport of gases, heat, and momentum between the earth's surface and the atmosphere [1, 2, 3]. Gas fluxes, emission and exchange rates are carefully characterized from single-point *in situ* measurements using permanent or mobile towers, or moving platforms such as automobiles, helicopters, airplanes, *etc*. The area that can be characterized by the eddy covariance method ranges extensively, from hundreds of square meters to tens of square kilometres, depending on the measurement height and surface conditions.

Since the early 1990s, this technique has been widely used by micrometeorologists across the globe

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for quantifying CO_2 emission rates from various natural, urban and agricultural ecosystems [1, 2, 3], including studies of agricultural carbon sequestration. Presently, over 600 eddy covariance stations are in operation in over 120 countries [3]. In the last 3-5 years, advancements in eddy covariance instrumentation and software have reached the point when they can be effectively used outside the area of micrometeorology, and can prove valuable for geological carbon capture, utilization and storage (CCUS), landfill emission measurements, high-precision agriculture, and other non-micrometeorological industrial and regulatory applications.

In the field of geological carbon capture, utilization and storage, the magnitude of CO_2 seepage fluxes depends on a variety of factors. Emerging projects utilize eddy covariance measurements to monitor large areas where CO_2 may escape from the subsurface, to detect and quantify CO_2 leakage, and to ensure the efficiency of CO_2 geological storage [5,6,7,8, 9,10,11,12].

Below we provide brief highlights of the eddy covariance method, its application to geological carbon capture, utilization and storage, key requirements, instrumentation and software, and review educational resources particularly useful for carbon sequestration research.

2. Eddy Covariance Method

2.1 Method description

Emission or consumption rates are often referred to as "flux" in ecosystem studies. The flux can be generally quantified as an amount of an entity that passes through a closed (*i.e.*, a Gaussian) surface per unit of time. With the eddy covariance method, the fluxes are computed from direct *in situ* measurements of the transport of gas from the surface into the atmosphere by the turbulent air flow moving above the surface. Such air flow can be imagined as a horizontal flow of numerous rotating eddies (Figure 1a). Each eddy has 3-D components, including vertical movement of the air. Conceptually, this is the framework for atmospheric eddy transport [3].

(a)

(b)

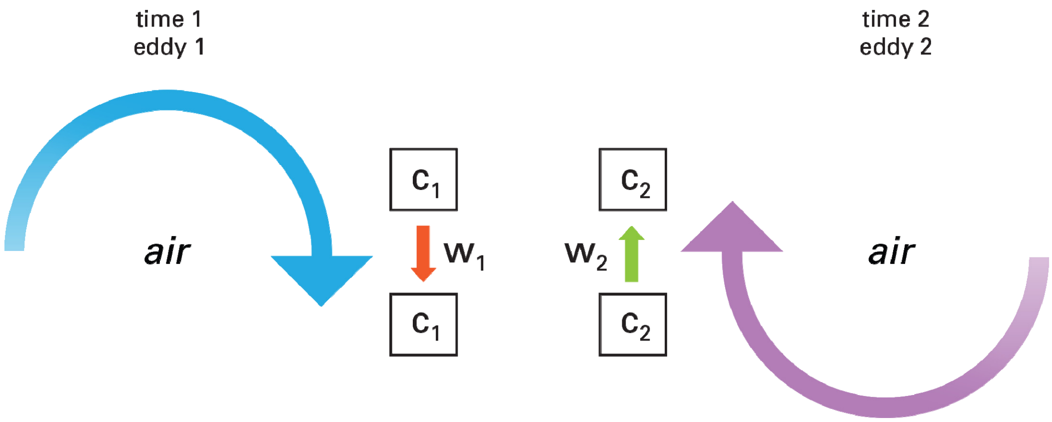

Fig. 1. (a) a diagram of air flow above the surface; (b) two eddies at a single point on the tower [3]

Figure 1b describes eddies at a single point on the tower. At one moment (time 1), eddy number 1 moves air parcel c_1 downward with the speed w_1. At the next moment (time 2) at the same point, eddy number 2 moves air parcel c_2 upward with speed w_2. Each air parcel has its own characteristics, such as gas concentration, temperature, humidity, *etc*. If these characteristics and the speed of the vertical air movement can be measured, one will know the vertical upward or downward fluxes of gas and water vapour concentrations, temperature, and humidity at this point.

For example, if at one moment we know that three molecules of CO_2 went up, and in the next moment only two molecules of CO_2 went down, then we know that the net flux over this time was upward, and equal to one molecule of CO_2. This is the general principle of eddy covariance measurements: covariance between the concentration of interest and vertical wind speed.

2.2. Method visualization

A simple way to visualize the key physical principle behind eddy covariance measurements is to first imagine an area that adds no molecules of the gas of interest to the mean flow, and then compare it to the same area that adds molecules into the flow. For example, let us imagine a mean flow that carries 3 molecules of CO_2 over the area of interest from left to right, as shown in Figure 2a. Since the measured area in the middle did not add anything to the flow, the eddy movements at the downwind measurement point on the right would carry, on average, 3 molecules upwards, and 3 molecules downward, with no net flux. Thus, over some time period, such as a 30-60 minutes, the eddy covariance station would measure a flux of zero from the area of interest in the middle.

Now let us imagine the same situation, but with the surface in the middle adding 2 molecules to the mean flow (Fig. 2b). Since the area in the middle added 2 molecules to the mean flow, the eddy motions at the downwind measurement point on the right would carry, on average, more molecules upward than downward, with some net CO_2 flux. Thus, over a time long period, such as 30-60 minutes, the eddy covariance station located on the right would measure some flux from the measured area in the middle.

Flux, therefore, is measured from the area of interest, which adds gas or energy to the mean flow or takes them away. It is also important to note that in this way we only measure the turbulent transport of the CO_2, and must have well-developed turbulence such that other mechanisms of transport are negligibly small. There are several additional important conditions and assumptions for confident measurements of turbulent flux related to the nature of the surface and air flow [1, 2, 3].

The ability of the eddy covariance method to provide direct measurements of half-hourly or hourly fluxes from a specific area added into the mean flow, integrated over such an area continuously throughout the years, and covering most of the days and significant portions of the nights, is an important practical advantage over other present flux measurement techniques.

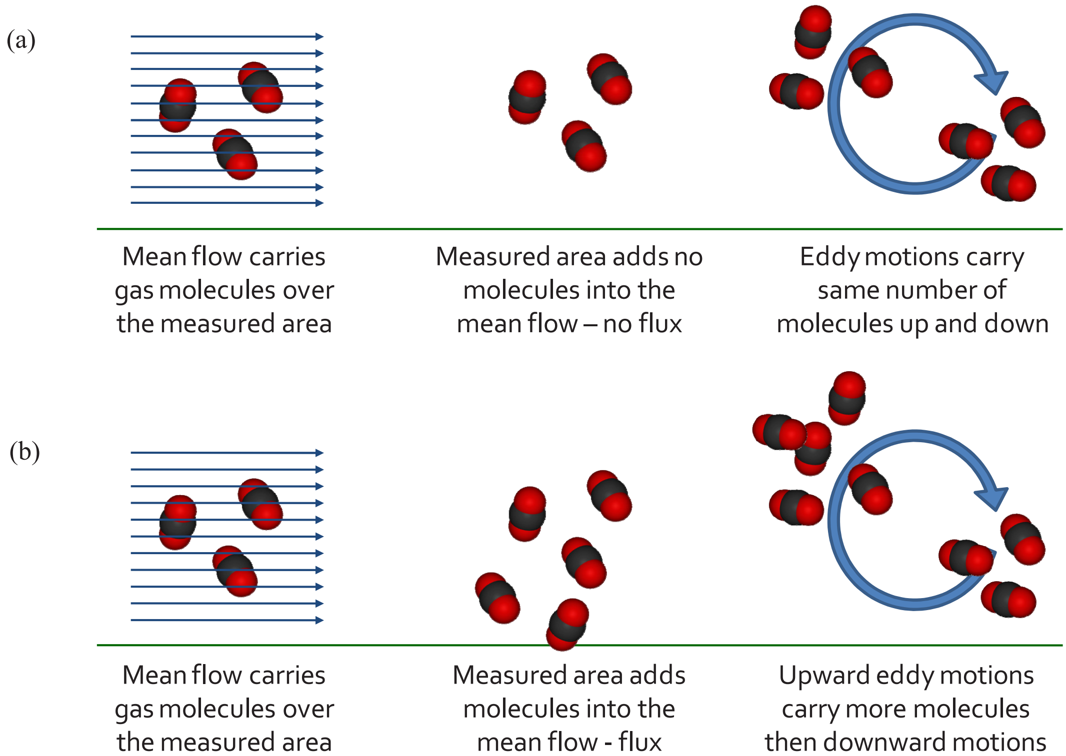

Fig. 2. (a) air flow over an area with no flux; (b) air flow over an area with flux [3]

2.3. Classical equation

Mathematically, the flux from the area of interest can be represented as a covariance between measurements of vertical velocity, the upward and downward movements, and the concentration of the entity of interest. In very simple terms, when we have turbulent flow, vertical flux is equal to a mean product of air density (ρ_a), vertical wind speed (w), and the dry mole fraction (s) of the gas of interest [1, 2, 3]:

$$Gas\ Emission\ Rate = \overline{\rho_a ws} \approx \overline{\rho_a}\,\overline{w's'} \tag{1}$$

The ρ_a is known from air temperature, humidity and barometric pressure, w is measured by a high-speed 3-dimensional sonic anemometer, and s is measured by a high-speed gas analyzer (*e.g.*, CO_2/H_2O,

CH_4, *etc.*)

The rightmost portion of Equation 1 is the result of a fairly complex derivation using Reynolds decomposition, where an instantaneous value for each member is presented as a product of an hourly or half-hourly mean (indicated by an over-bar symbol), and an instantaneous deviation from the mean (indicated by a prime symbol). As a result, the hourly or half-hourly fluxes, or emission rates, are computed using instantaneous data, usually recorded 10-20 times per second. A more detailed basic derivation of the classical eddy covariance equation is provided in pages 18-20 of [3], and full derivation are provided in [1] and [2].

2.4 Instrumentation

Variables required by all eddy covariance applications, including industrial applications and CCUS, are those describing the turbulent transport itself, such as three components of the 3-dimensional wind speed (*u, v, w*), sonic temperature (T_s), concentration of the gas of interest (for example, CO_2 or CH_4), and water vapour. These measurements have to be quite fast to be able to compute the gas flux, and are captured by a basic eddy covariance station. The instrumentation of a basic eddy covariance station includes a 3-dimensional sonic anemometer and a gas analyzer. These stations are used primarily for regulatory, monitoring and inventory purposes, and in some agricultural and industrial applications, including CCUS.

The stations can additionally be equipped with instrumentation to measure weather variables (*e.g.*, mean air temperature, relative humidity, wind speed, direction, precipitation amounts, *etc.*). These variables, measured at the same location and at the same time, are used to help interpret the flux data, and to fill-in potential gaps in data.

The fully equipped eddy covariance stations, usually deployed in ecosystem studies, may also have gas and water vapour concentration profiles below the flux measurement level, solar radiation data (*e.g.*, net radiation, incoming and outgoing shortwave and photosynthetically active radiation, *etc.*), soil heat flux, and soil temperature and moisture data.

(a) (b) (c)

Fig. 3. (a) standard instrumentation on the eddy covariance tower; (b) stationary tower measuring emissions of CO_2, CH_4 and H_2O; (c) mobile tower measuring emissions of CO_2, CH_4 and H_2O

2.5 Data processing

Processing eddy covariance data requires flexible software that fits a wide range of experimental designs and sampling conditions. Multiple automated packages are available for data collection, and recently, several packages have become available for comprehensive data processing with advanced options and user-friendly interface. One such program is the fully-supported open-source software, EddyPro® [3].

Throughout the process of data collection it is imperative to keep the original raw data files. These are large in volume due to 10 or 20 Hz data collection, so provisions should be made to accommodate and archive them over the long term.

The major steps in flux processing applied by the software include: converting signals from voltages to physical units, de-spiking the raw data, applying calibration coefficients, applying required corrections to the raw data, averaging data over 0.5 to 4 hour periods, applying required corrections to the averaged data, conducting quality control, filling-in missed periods, and integrating the averaged data over the long term.

3. Industrial applications and CCUS

Industrial applications usually focus on very concrete goals of quantifying emissions of gases, capture and line efficiencies, leakage rates over industrial zones, geological carbon sequestration and hydraulic fracturing (*e.g.,* fracking) sites, landfills, and along pipelines. Industrial use of the eddy covariance method is a relatively new area. In the past, measurements were done with a range of modelling techniques (from emission indices and remote sensing, to plume modelling) and more direct measurements (*e.g*., stack detectors, chamber techniques, flask sampling, *etc*.).

In CCUS specifically, the eddy covariance method was tested and recommended since the early 2000s [7, 11, 13], but was not widely used due to methodological complexities. In the last 3-5 years, advancements in methodology, instrumentation and automated software allowed eddy covariance to be effectively used in many industrial and regulatory applications [3, 4, 9], including geological CCUS, providing a direct way to measure and calculate emissions.

Major regulatory bodies, such as IPCC and the U.S. Department of Energy, and large industrial projects now utilize eddy covariance to detect and quantify CO_2 leakage in CCUS sites, and assure gas storage efficiency [5, 6, 10, 12, 13, 14]. The 2012 manual from the U.S. Department of Energy [14] “Best Practices for Monitoring, Verification, and Accounting of CO_2 Stored in Deep Geologic Formations” describes eddy covariance as one of their recommended methods (details at www.netl.doe.gov/technologies). These recommendations are similar to those from 2006 IPCC/UNEP guidelines “IPCC Guidelines for National Greenhouse Gas Inventories. Volume 2, Energy“ updated in 2011 [13], and available at www.ipcc-nggip.iges.or.jp/public/2006gl.

Modern eddy covariance stations allow direct automated measurements of the gas emissions from a specific territory reported in weight or volume of gas per unit area per unit time. The required stations, in general, may be much simpler than those used in scientific applications. Most supporting variables are not necessary because the purpose of the project is to quantify the emission, adjust the industrial or management process or design, and determine if there is a resulting improvement. However, industrial applications often involve large territories with complex surfaces, so more than one eddy covariance station may be required for confident measurements of fluxes from these large areas.

One example of a novel use of the eddy covariance method in industrial applications is a carbon capture, utilization and storage project by the Midwest Geological Sequestration Consortium at their

Decatur, Illinois site [4, 8, 11, 15]. One million tons of CO_2 captured from a nearby ethanol plant are to be injected at 1,000 tons per day over a three year period into the 1,500 ft. thick sandstone, at a depth of about 6,500 ft. The basic solar-powered eddy covariance station shown in Figures 4a and b consists of a 3-D sonic anemometer and a fast CO_2/H_2O gas analyzer, and is augmented with a mean wind speed and wind direction sensor. Measurements are conducted at this site concurrently with chamber techniques and other measurement and modelling methods (details are available at www.sequestration.org).

(a) (b)

Fig. 4. (a) solar-powered eddy covariance station at CCUS site near Decatur, Illinois; (b) setting up the station.

4. Conclusions

The eddy covariance method is a micrometeorological technique for direct high-speed measurements of the transport of gases and energy between the land or water surface and the atmosphere. This method allows the observations of gas transport scales from 20-40 times per second to multiple years. It represents gas exchange over a large area, and not just at a single spot, and corresponds to gas exchange from the whole surface, not just the soil or water layer.

The eddy covariance method is now recognized as a useful tool in regulatory and industrial applications, including CCUS [4,5,6,7,8,9,10,11,12,13,14,15,16]. Particularly, it may be used as an effective way to continuously monitor large areas before and after the CO_2 injection, to locate and quantify leakages, improve storage efficiency, and for other CCUS characterizations.

Although eddy covariance is one of the most direct and defensible ways to measure and calculate turbulent fluxes, and complete automated stations are available in ready-to-use packages, the method is mathematically complex, and requires careful setup, execution and data processing tailor-fit to a specific site and project. With this in mind, step-by-step instructions were created in [3] to introduce a novice to the conventional eddy covariance technique, and to assist in further understanding of the method through more advanced references such as graduate-level textbooks, flux networks guidelines, journals and technical papers. A free open-source automated software package [17] with a user-friendly interface was developed accordingly for automated computing of final fully corrected CO_2 emission numbers.

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